TECHNICAL REPORT NO. 6-570

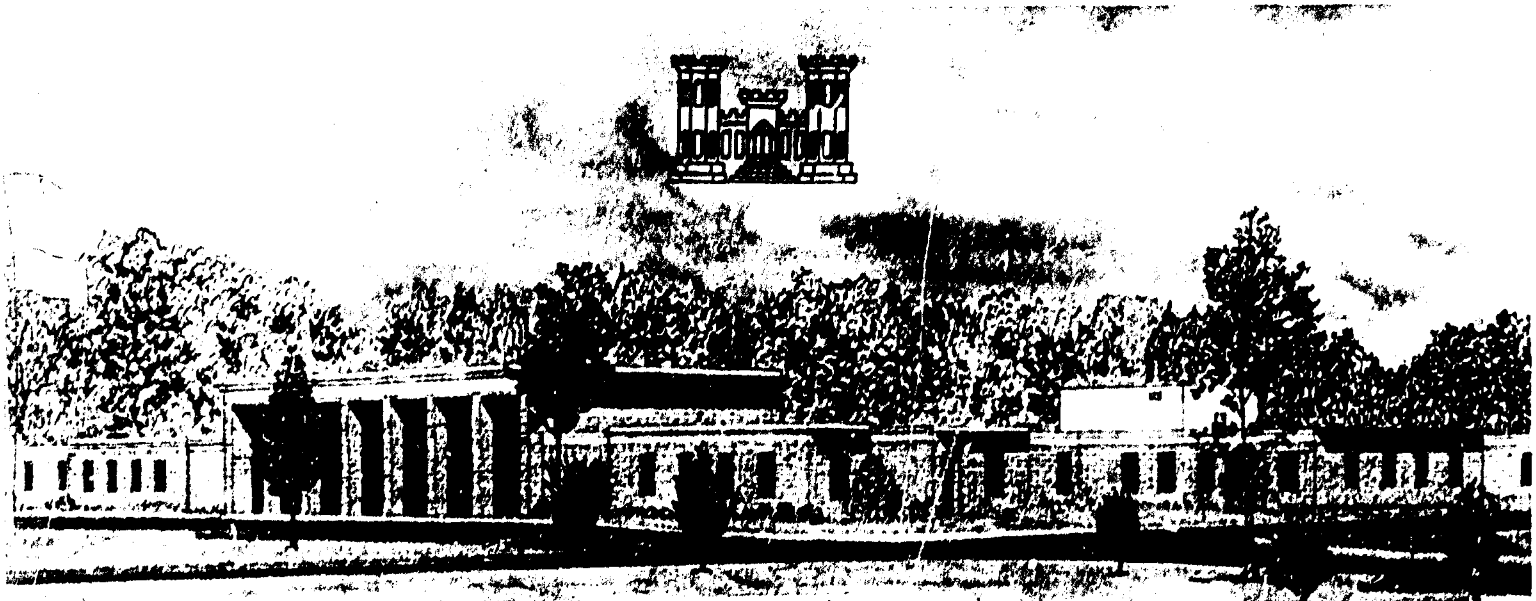
DURABILITY AND BEHAVIOR OF PRESTRESSED CONCRETE BEAMS

Report 3

LABORATORY TESTS OF WEATHERED PRETENSIONED BEAMS

by

E. C. Roshore



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13. ABSTRACT

The work described ~~herein~~ ~~involved~~ laboratory tests which were conducted on four prestressed concrete beams which had been exposed to tidal weathering for a considerable period of time. Two of the beams had been exposed in an unloaded condition at the Treat Island, Maine, severe weathering exposure station and the other two had been exposed for 9 years in a flexurally loaded condition at the St. Augustine, Florida, mild weathering exposure station. The laboratory tests conducted on these beams consisted of the examination and tensile testing of the steel prestressing strands after removal from the beams and tests for depth of carbonation and chloride penetration in the test beams. The steel prestressing strands were found to be corroded externally for 20 to 100 percent of their length. Internal strand corrosion was generally more extensive than the external corrosion; the corrosion seemed to progress along the center wire of each strand. Only 8 of the 25 strand sections tested met the tensile strength and elongation requirements of ASTM Designation: A 416-68. Corrosion on the steel strands at the ends of all beams showed that the epoxy pads used as end protection were not effective in protecting the ends of the strands. Depth of carbonation tests indicated that carbonation was not a factor in the corrosion of the steel strands. Depth of chloride penetration tests revealed that sufficient chlorides were present in the test beams to cause corrosion on the prestressing strands. The steel strands taken from the St. Augustine beams were in poorer condition than those from the Treat Island beams. The major cause of strand corrosion in the Treat Island beams was the inadequacy of the epoxy pad end protection and subsequent spalling. The major cause of strand corrosion in the St. Augustine beams appeared to be the cracking in the beams which resulted from the initial flexural loading.

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FOREWORD

This investigation forms a part of Item 031 of the Civil Works Engineering Study Program. This phase of the investigation was authorized by the Office, Chief of Engineers, in a letter dated 16 December 1968, subject: Examination of Treat Island Exposure Specimens, and in a first indorsement to a letter dated 16 April 1969, subject: Project Plan for Laboratory Tests of Pretensioned Concrete Beams Returned from St. Augustine, Florida.

The test program was carried out by the Concrete Division of the U. S. Army Engineer Waterways Experiment Station (WES) under the direction of Messrs. Bryant Mather, R. V. Tye, Jr., J. M. Polatty, and E. E. McCoy, Jr. This report was prepared by Mr. E. C. Roshore.

Directors of the WES during the conduct of this investigation and preparation of this report were COL John R. Oswalt, Jr., CE, COL Levi A. Brown, CE, and COL Ernest D. Peixotto, CE. Messrs. J. B. Tiffany and F. R. Brown were Technical Directors.

CONTENTS

CONVERSION FACTORS, BRITISH TO METRIC UNITS OF MEASUREMENT

British units of measurement used in this report can be converted to metric units as follows:

Multiply	By	To Obtain
gallons (U. S.) per bag of cement	88.781398	cubic centimeters per kilogram of cement
inches	25.4	millimeters
pounds (force)	0.45359237	kilograms (force)
	4.448222	newtons
pounds (force) per square inch	0.070307	kilograms (force) per square centimeter
	6.894757	kilonewtons per square meter

SUMMARY

This report is the third in a series describing a study which is being conducted to develop information on the durability of prestressed concrete beams. The work described herein involved laboratory tests which were conducted on four prestressed concrete beams which had been exposed to tidal weathering for a considerable period of time. Two of the beams had been exposed in an unloaded condition for 10 years at the Treat Island, Maine, severe weathering exposure station and the other two had been exposed for 9 years in a flexurally loaded condition at the St. Augustine, Florida, mild weathering exposure station. The two St. Augustine beams had been loaded flexurally at installation to 189 percent of prestress in order to induce cracking.

The laboratory tests conducted on these beams consisted of the examination and tensile testing of the steel prestressing strands after removal from the beams and tests for depth of carbonation and chloride penetration in the test beams.

The significant findings of the laboratory tests were:

- *a.* The steel prestressing strands removed from the beams were corroded externally for 20 to 100 percent of their length. Internal strand corrosion was generally more extensive than the external corrosion; the corrosion seemed to progress along the center wire of each strand.
- *b.* Only 8 of the 25 strand sections tested met the tensile strength and elongation requirements of ASTM Designation: A 416-68.
- *c.* Corrosion on the steel strands at the ends of all beams showed that the epoxy pads used for end protection were not effective in protecting the ends of the strands.
- *d.* Depth of carbonation tests indicated that carbonation was not a factor in the corrosion of the steel strands.
- *e.* Depth of chloride penetration tests revealed that sufficient chlorides were present in the test beams to cause corrosion on the prestressing strands.
- *f.* The steel strands taken from the St. Augustine beams were in poorer condition than those from the Treat Island beams.
- *g.* The major cause of strand corrosion in the Treat Island beams was found to be the inadequacy of the epoxy pad end protection and subsequent spalling.
- *h.* The major cause of strand corrosion in the St. Augustine beams appeared to be the cracking in the beams which resulted from the initial flexural loading.

DURABILITY AND BEHAVIOR OF PRESTRESSED CONCRETE BEAMS

LABORATORY TESTS OF WEATHERED PRETENSIONED BEAMS

PART I: INTRODUCTION

BACKGROUND

1. This investigation was begun in 1956 to develop information on the durability and behavior of prestressed concrete beams. In 1958 and 1959, pretensioned concrete beams were installed at outdoor tidal exposure stations at Treat Island, Maine, and St. Augustine, Florida. In Maine, the beams were subjected to freezing in air and thawing in sea water, and in Florida to the attack of the dissolved salts in warm sea water. Report 1 of this series[1] describes the test beams which were exposed and reports the progress of the investigation to July 1960. Report 2 of this series[2] gives the results to July 1966 of the phase of the investigation concerned with posttensioned concrete beams.

PURPOSE OF NVESTIGATION

2. The primary purpose of this phase of the investigation was to determine the condition of steel prestressing strands in selected weathered prestressed beams from the Treat Island and St. Augustine exposures. The following additional factors were also under study: (*a*) depth of carbonation in test beams and (*b*) depth of chloride penetration in test beams.

SCOPE OF INVESTIGATION

3. The investigation consisted essentially of visual examination and laboratory tests of prestressing strands and concrete taken from four weathered prestressed beams which were returned from either Treat Island or St. Augustine. The following specific tests were performed on some or all of the prestressing strands or concrete taken from the four test beams:

a. Examination of steel prestressing strands for extent of corrosion.

b. Determination of tensile strength, elongation at failure, and stress-strain characteristics of steel prestressing strands.

c. Tests for depth of carbonation in beam.

d. Tests for depth of chloride penetration into beam.

PART II: TEST SPECIMENS

4. The pretensioned concrete beams in this study were of rectangular cross section (4-1/2 by 9 in.*) and were 81 in. long. Each beam contained nine 1/4-in. (1 by 7) prestressing strands located as shown in fig. 1. The beams were made of good quality air-entrained concrete using

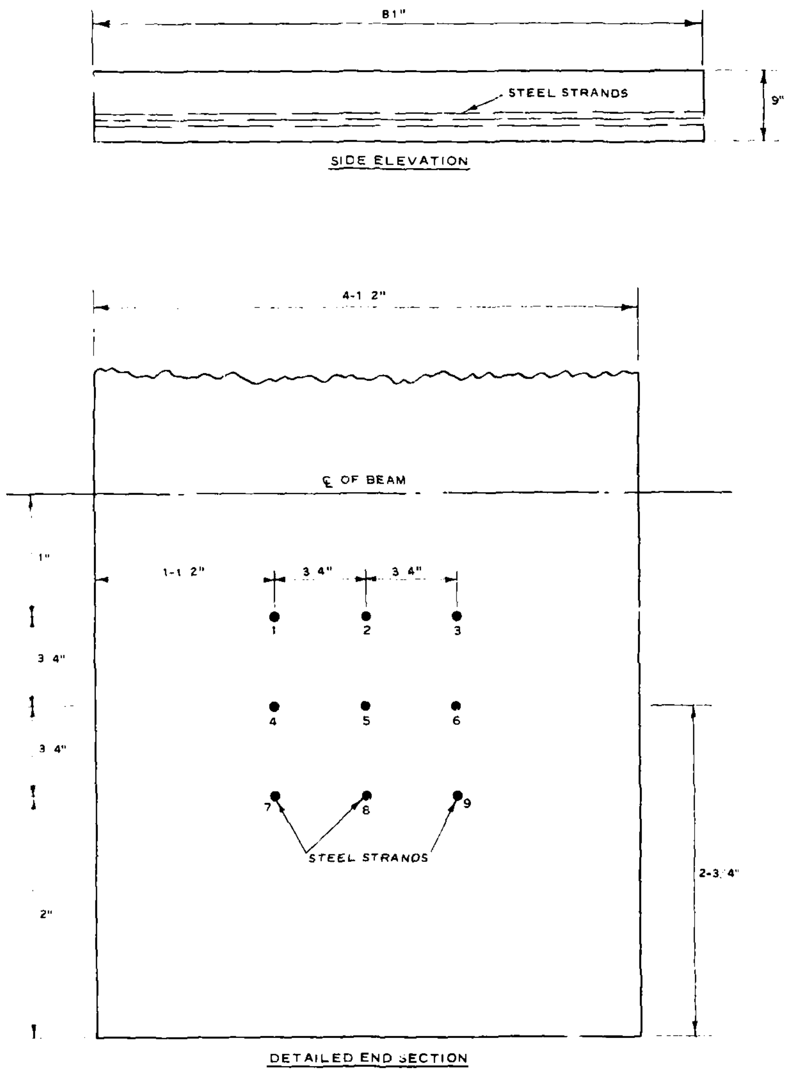

Fig. 1. Detailed section of pretensioned concrete beam

* A table of factors for converting British units of measurement to metric units is presented on page ix.

limestone aggregates. Physical properties of the concrete mixture were:

Maximum Size Coarse Aggregate in.	Entrained Air, %	Nominal Compressive Strength at 28 Days, psi	Slump in.	Water-Cement Ratio gal/bag
3/4	4.5 $\pm$ 0.5	6000	1-3/4 $\pm$ 1/2	5.85

The ends of the steel strands were cut to be flush with the ends of the beams and were protected at each beam end with a pad of epoxy approximately 3 by 5 by 1/2 in. thick.

BEAMS RETURNED FROM TREAT ISLAND

5. Pretensioned beams 4 and 8 were installed (in an unloaded condition) on the beach at Treat Island in October 1958 and returned to the laboratory in September 1968 after 10 winters of tidal exposure (1326 cycles of freezing and thawing).

6. The steel prestressing strands in beam 4 had only been stressed to approximately 1 percent of their ultimate strength during beam fabrication; this is essentially a no-prestress condition. The strands in beam 8 were pretensioned to approximately 70 percent of their ultimate strength during the beam fabrication.

Beam 4

7. Photograph 1*a* and *b* shows beam 4 on the beach at Treat Island, as viewed from its landward and seaward ends, respectively, while it was under exposure. The protective epoxy pads had come off of both ends of the beam and there was considerable spalling (photograph 2*a* and *b*).

Beam 8

8. Photograph 1*c* and *d* gives the landward and seaward views of beam 8 under exposure. (Beam 8 is on the left in photograph 1*c* and on the right in photograph 1*d*.) The protective epoxy pads had come off of both ends and there was considerable spalling, especially on the landward end (photograph 2*c* and *d*).

BEAMS RETURNED FROM ST. AUGUSTINE

9. Pretensioned beams 10 and 18 were installed in a loaded condition on the St. Augustine exposure rack in October 1959 and returned to the laboratory in the spring of 1969 after 9-1/2 years of tidal exposure.

10. The beams both contained steel prestressing strands which had been tensioned to 70 percent of their ultimate strength during beam fabrication. On installation at St. Augustine, the beams were yoked together using a spring-and-yoke loading frame with pipe rollers at third-points and loaded flexurally to 189 percent of prestress. This was essentially a load to cracking, as numerous cracks were opened up in the beams during the loading. During the reloading operation (to adjust load to its proper value) in 1968, beam 18 failed. Photograph 3 shows the two beams after the failure of beam 18. The epoxy pads at the ends of beams 10 and 18 were present but not effective since rust spots which were visible through the pad indicated that corrosion had started at the ends of the strands in both beams (see photograph 4).

PART III: TESTS AND RESULTS

11. Tests conducted on pretensioned beams returned from Treat Island and St. Augustine were:

a. Examination of steel prestressing strands.

b. Determination of tensile strength and elastic properties of steel strands.

c. Tests for depth of carbonation.

d. Tests for depth of chloride penetration.

EXAMINATION OF STRANDS

12. The condition of each of the steel prestressing strands in each of the beams was determined by visual examination after removing each strand from the concrete. The extent of external corrosion along strands was noted, and portions of strands were unraveled to reveal the extent of corrosion on the inner wires.

13. The location of the steel strands in each concrete beam is shown in fig. 1. Three strands are in each of three rows: the strands in the row nearest the top of the beam as cast are numbered 1, 2, and 3; the middle row 4, 5, and 6; and the bottom row 7, 8, and 9. Each strand is a nominal 1/4-in.-diam strand made up of seven wires, a center wire with six others around it.

14. In evaluating the corrosion existing on the surface of the steel strands, it was necessary to establish a definition of terms as follows:

Extent of Corrosion	% of Surface Area of Strand Coated with Corrosion Products
Heavy	80-100
Moderate	30-80
Light	0-30

Treat Island Beams

15. *Beam 4.* The following portions of the steel strands from beam 4 were uncovered by spalling and were therefore exposed directly to the elements (photograph 2*a* and *b*).

Strand	Inches of Strand Exposed	
	Seaward End	Landward End
1	Tip only	Tip only
2	Tip only	Tip only
3	Tip only	Tip only
4	Tip only	1
5	Tip only	1/4
6	Tip only	1
7	6	1
8	5-3/4	1/4
9	5-1/2	1-1/2

16. The following subparagraphs give the results of the examination of the steel strands from beam 4.

a. *Strand 1.*

(1) *Landward end.* External corrosion extended to 9 in. from end (heavy = 4-1/2 in., moderate = 4-1/2 in.).

(2) *Seaward end.* External corrosion existed for 7 in. from end (heavy = 1 in., moderate = 5 in., light = 1 in.).

(3) *Rest of strand.* At two points, 8 and 11 in. from the seaward end, 1/2-in.-long rust spot occurred.

(4) *Internal versus external.* Internal corrosion extended up to 12 in. from the seaward end (on center wire). The corrosion on the center wire extended farther into the beam than on the other six wires. For the landward end, internal corrosion was essentially equal to external corrosion; the center wire was corroded no more than the others.

b. *Strand 2.*

(1) *Landward end.* External corrosion extended for 19 in. from end (heavy = 13 in., moderate = 4 in., light = 2 in.).

(2) *Seaward end.* External corrosion existed for 3 in. from end (moderate = 2 in., light = 1 in.).

(3) *Rest of strand.* There were three 1/2-in.-long spots located 6, 8-1/2, and 10 in. from the seaward end.

(4) *Internal versus external.* Internal corrosion extended farther from the seaward end than did external corrosion (about 1 in. more), and the center wire had more corrosion than did the other wires. The internal corrosion on the landward end of this strand extended for about 29 in. from the end, with the corrosion being greater on the center wire.

c. *Strand 3.* This strand was unraveled for its full length.

(1) *Landward end.* External corrosion extended 18 in. from end (heavy = 9 in., moderate = 7 in., light = 2 in.).

(2) *Seaward end.* There was light external corrosion for about 1/8 in. from end.

(3) *Rest of strand.* Two 1/2-in.-long rust spots occurred at distances of 2 and 5 in. from the seaward end.

(4) *Internal versus external.* Light internal rusting occurred up to 25 in. from the seaward end, and the center wire had more corrosion. Internal corrosion extended to 21-1/2 in. from the landward end on the center wire, which had more corrosion than the others.

d. *Strand 4.*

(1) *Landward end.* External corrosion occurred for 7 in. from end (heavy = 5 in., moderate = 1 in., light = 1 in.).

(2) *Seaward end.* External corrosion existed for 6 in. from end (heavy = 1/2 in., moderate = 3-1/2 in., light = 2 in.).

(3) *Rest of strand.* One 1-in.-long rust spot occurred about 11-1/2 in. from the seaward end, and one 4-in.-long rust spot existed at midlength (40 in. from seaward end).

(4) *Internal versus external.* Internal corrosion for both ends was essentially equal to external corrosion, with corrosion on the center wire being equal to the others.

e. *Strand 5.*

(1) *Landward end.* External corrosion existed for 12 in. from the end

(heavy = 8 in., moderate = 2 in., light = 2 in.). The first 6 in. of this strand was heavily coated with corrosion products.

(2) *Seaward end.* Only 1/2 in. of external corrosion existed on the seaward end, with the corrosion being equally divided between moderate and light.

(3) *Rest of strand.* Four 1-in.-long rust spots occurred externally at distances of 3-1/2, 6, 8, and 13 in. from the seaward end.

(4) *Internal versus external.* Rust spots occurred internally on all wires on the seaward portion, with the center wire exhibiting more corrosion. It was apparent that rust started on the center wire and extended to the other wires. Internal corrosion of the landward end was equal to external corrosion, with the center-wire corrosion essentially equal to the corrosion on the other wires.

f. *Strand 6.*

(1) *Landward end.* External corrosion (photograph 5*a*) extended for 9 in. from end (heavy = 4 in., moderate = 2 in., light = 3 in.).

(2) *Seaward end.* There was only 1/2 in. of external corrosion (moderate).

(3) *Rest of strand.* A 14-in.-long externally corroded section occurred 29 in. from the seaward end.

(4) *Internal versus external.* Internal corrosion of the seaward end was greater than external, with corrosion occurring up to 2 in. from the seaward end. Center-wire corrosion was no greater than corrosion on the other wires. Internal corrosion was also greater than external corrosion for the landward end, with corrosion of the center wire extending to 10 in. from the beam end.

g. *Strand 7.*

(1) *Landward end.* External corrosion existed for about 7-3/4 in. from the end (heavy = 3/4 in., moderate = 3 in., light = 4 in.).

(2) *Seaward end.* External corrosion existed for 7 in. from end (heavy = 5 in., moderate = 1 in., light = 1 in.).

(3) *Rest of strand.* Three 1-1/2-in.-long externally corroded sections occurred at distances of 17, 23, and 36 in. from the seaward end.

(4) *External versus internal.* Internal corrosion was essentially equal to external corrosion, and the center wire was not corroded more than the others.

h. *Strand 8.* This strand was unraveled for its full length.

(1) *Landward end.* External corrosion extended 1-1/2 in. from end (heavy = 1/2 in., moderate = 1/2 in., light = 1/2 in.).

(2) *Seaward end.* External corrosion existed for 8-1/2 in. from end (heavy = 3 in., moderate = 4 in., light = 1-1/2 in.).

(3) *Rest of strand.* External corrosion occurred at 18 in. (6 in. long) and at 37 in. (18 in. long) from the seaward end.

(4) *External versus internal.* Internal corrosion at the seaward end was greater than external corrosion, with numerous intermittent rust spots occurring all along the wires and with the greater number closer to the seaward end. The corrosion was greater on the center wire, indicating that the corrosion was progressing along the center wire, even though it was not continuous. For the landward end, internal corrosion was slightly greater than external corrosion, but the extent of internal corrosion was not as great as on the seaward end. The center wire on the landward end did not appear to be more corroded than the other wires.

i. *Strand 9.*

(1) *Landward end.* External corrosion (photograph 5*b*) extended for 6 in. from end (heavy = 2-1/2 in., moderate = 1-1/2 in., light = 2 in.).

(2) *Seaward end.* External corrosion occurred for 9 in. from end (heavy = 4 in., moderate = 4-1/2 in., light = 1/2 in.).

(3) *Rest of strand.* One 19-in.-long rusted section occurred at 37 in. from the seaward end.

(4) *Internal versus external.* Internal corrosion was equal to external with all wires corroded equally.

17. The following tabulation summarizes the external corrosion found on the 81-in.-long steel strands in beam 4.

	Total External Corrosion		External Corrosion Associated with Ends of Beam		External Corrosion Not Associated with Ends of Beam	
Strand	in.	% of Total Length of Strand	in.	% of Total External Corrosion	in.	% of Total External Corrosion
1	17	21	16	94	1	6
2	23-1/2	29	22	94	1-1/2	6
3	19-1/8	24	18-1/8	95	1	5
4	18	22	13	72	5	28
5	16-1/2	20	12-1/2	76	4	24
6	23-1/2	29	9-1/2	40	14	60
7	19-1/4	24	14-3/4	77	4-1/2	23
8	34	42	10	29	24	71
9	34	42	15	44	19	56

18. Corrosion seemed to start at the ends of the beam and progress toward the center of the beam both externally and internally. The internal corrosion apparently progressed along the center wire; this was true in six of the nine strands. Strands 6, 8, and 9 had considerable corrosion in the interior of the beam which was not contiguous to the corrosion at the ends of the strands. This corrosion is evidently not related to the progressive corrosion from the ends and was probably related to poor bonding of the strands at these locations.

19. An examination of the concrete adjacent to the steel strands indicated that products of corrosion existed on the concrete adjacent to the strands in areas where the strand corrosion occurred. The extent of the products present depended upon the degree of corrosion of the strand. All heavy staining of the concrete occurred at the ends of the beams where the corrosion was heaviest. Light corrosion occurred at several places in the interior of the beam, but corrosion products in these cases were restricted to the immediate vicinity of the strand (photograph 6*a*). On the seaward end of the beam, an area 2-1/2 in. square containing the nine strands was stained with corrosion products; the extent to which this area extended into the beam from the end depended on the corrosion of each individual strand which the concrete surrounded. The heavy staining extended generally for about 4 to 6 in. on this seaward end. The largest deposit of corrosion products occurred close to strands 7 and 8 on the seaward end (see photograph 6*b*). This deposit is about 1-1/2 in. in diameter and 2 in. long. Staining of the concrete on the landward end occurred throughout a 2-in.-square section around the strands; this stained section extended

about 6 to 7 in. in from the end of the beam.

20. *Beam 8.* The following portions of the steel strands from beam 8 were uncovered by spalling and were therefore exposed directly to the elements (photograph 2*c* and *d*).

	Inches of Strand Exposed	
Strand	Seaward End	Landward End
1	Tip only	3
2	Tip only	Tip only
3	Tip only	1
4	Tip only	9
5	Tip only	7
6	1/4	7
7	1	15*
8	Tip only	15*
9	1/4	15*

* Approximately 7 in. of each of these strands was missing; this is included in exposed length.

21. The following subparagraphs give the results of the examination of the steel strands from beam 8.

a. *Strand 1.*

(1) *Landward end.* Continuous external corrosion existed for 33 in. from the end (heavy = 10 in., moderate = 18-1/2 in., light = 4-1/2 in.).

(2) *Seaward end.* Continuous external corrosion extended for 7-1/4 in. from end (heavy = 1/4 in., moderate = 5 in., light = 2 in.).

(3) *Rest of strand.* Intermittent light or moderate corrosion occurred throughout the beam for a total of 11 in. (moderate = 3-1/2 in., light = 7-1/2 in.). This total includes moderate corrosion which occurred in a 2-in. length 31 in. from the seaward end and in a 1-1/2-in. length 25 in. from the seaward end.

(4) *Internal versus external.* Internal corrosion extended farther than the external corrosion, with the center wire being the most heavily corroded.

b. *Strand 2.*

(1) *Landward end.* Continuous external corrosion extended for 19 in. from end (heavy = 14 in., moderate = 4 in., light = 1 in.).

(2) *Seaward end.* Continuous external corrosion extended only 2 in. from end (moderate = 1/2 in., light = 1-1/2 in.).

(3) *Rest of strand.* Intermittent moderate or light corrosion occurred for a total of 9-1/2 in. (moderate = 5-1/2 in., light = 4 in.). This includes a 1-1/2-in.-long spot of moderate corrosion 32 in. from the landward end.

(4) *Internal versus external.* Internal corrosion extended at least 4 in. farther than the external corrosion, with the center wire having the most corrosion.

c. *Strand 3.*

(1) *Landward end.* Continuous external corrosion extended for 25 in. from end (heavy = 11-1/2 in., moderate = 10-1/2 in., light = 3 in.).

(2) *Seaward end.* Continuous external corrosion occurred for 2-1/2 in. (moderate = 1/2 in., light = 2 in.).

(3) *Rest of strand.* Intermittent moderate or light corrosion occurred for about 11 in. (moderate = 5 in., light = 6 in.).

(4) *Internal versus external.* This strand was unraveled for its full length. The

center wire was either heavily or moderately corroded for the entire length of the strand, the other wires were corroded on surfaces which were in contact with the center wire.

d. *Strand 4.*

(1) *Landward end.* Continuous external corrosion extended for 30 in. from the end (heavy = 16 in., moderate = 12 in., light = 2 in.).

(2) *Seaward end.* Continuous external corrosion existed for 3 in. from end (moderate = 1/2 in., light = 2-1/2 in.).

(3) *Rest of strand.* Intermittent moderate or light corrosion occurred for a total of 14 in. (moderate = 4 in., light = 10 in.).

(4) *Internal versus external.* Internal corrosion extended farther than external corrosion, with the center wire being the most heavily corroded.

e. *Strand 5.*

(1) *Landward end.* External corrosion was continuous for 17-1/2 in. (heavy = 10 in., moderate = 7 in., light = 1/2 in.).

(2) *Seaward end.* Continuous external corrosion extended for 5-1/2 in. from the end (heavy = 1/2 in., moderate = 4 in., light = 1 in.).

(3) *Rest of strand.* Intermittent moderate or light corrosion occurred for 19 in. (moderate = 11 in., light = 8 in.). Several 1- to 2-in.-long spots of moderate corrosion existed within 40 in. of the landward end.

(4) *Internal versus external.* Internal corrosion extended at least 5 in. farther than the external corrosion; this corrosion was principally along the center wire.

f. *Strand 6.*

(1) *Landward end.* Continuous external corrosion (photograph 5c) existed for 24 in. from the landward end (heavy = 11 in., moderate = 12 in., light = 1 in.).

(2) *Seaward end.* External corrosion was continuous for 5 in. (heavy = 1/2 in., moderate = 2-1/2 in., light = 2 in.).

(3) *Rest of strand.* Seven inches of intermittent light corrosion occurred on the remainder of the strand.

(4) *Internal versus external.* This strand was unraveled completely, and the center wire was found to be heavily or moderately corroded for its entire length. Other wires were corroded on surfaces which were in contact with the center wire.

g. *Strand 7.*

(1) *Landward end.* External corrosion was continuous for 31 in. from the end (heavy = 19 in., moderate = 9 in., light = 3 in.). Approximately 7 in. of this strand was gone, having corroded through and broken off; this length is tabulated as heavy corrosion. The strand remaining had become unraveled for 7 in.

(2) *Seaward end.* Continuous external corrosion existed for 5 in. from the end (heavy = 1 in., moderate = 1 in., light = 3 in.).

(3) *Rest of strand.* Intermittent light corrosion occurred in the amount of 13 in.

(4) *Internal versus external.* This strand was unraveled completely, and the center wire was found to be heavily or moderately corroded for its entire length. Other wires were similarly corroded on surfaces which were in contact with the center wire.

h. *Strand 8.*

(1) *Landward end.* Continuous external corrosion was present for 27 in. from

the end (heavy = 20 in., moderate = 6 in., light = 1 in.). About 7 in. at the end of this strand was missing and the strand had become unraveled for another 3 or 4 in.

(2) *Seaward end.* External corrosion was continuous for 8-1/2 in. from the end (moderate = 5 in., light = 3-1/2 in.).

(3) *Rest of strand.* Ten inches of light corrosion occurred intermittently over the external surfaces.

(4) *Internal versus external.* Internal corrosion extended up the center wire for at least 3 in. beyond the external corrosion.

i. Strand 9.

(1) *Landward end.* External corrosion (photograph 5*d*) was continuous for 22 in. from the end (heavy = 17 in., moderate = 3 in., light = 2 in.). Seven inches of this strand had corroded off and the strand had become unraveled for another 7 in.

(2) *Seaward end.* External corrosion was continuous for only 1 in. from the end (moderate = 1/2 in., light = 1/2 in.).

(3) *Rest of strand.* Nine inches of light corrosion occurred intermittently on the external surface of the strand.

(4) *Internal versus external.* Internal corrosion existed on the center wire and the six other wires for at least 6 in. beyond the extent of the external corrosion. The center wire had the greatest corrosion.

22. The following tabulation summarizes the external corrosion found on the steel strands in beam 8.

Strand	Total External Corrosion, in.	Total External Corrosion, % of Total Length of Strand	External Corrosion Associated with Ends of Beam, in.	External Corrosion Associated with Ends of Beam, % of Total External Corrosion	External Corrosion Not Associated with Ends of Beam, in.	External Corrosion Not Associated with Ends of Beam, % of Total External Corrosion
1	51-1/4	63	40-1/4	79	11	21
2	30-1/2	38	21	69	9-1/2	31
3	38-1/2	48	27-1/2	71	11	29
4	47	58	33	70	14	30
5	42	52	23	55	19	45
6	36	44	29	81	7	19
7	49	60	36	73	13	27
8	45-1/2	56	35-1/2	78	10	22
9	32	40	23	72	9	28

23. The steel strands in beam 8 had been uncovered through spalling to a greater degree than the strands in beam 4 and therefore exhibited more surface corrosion. The corrosion seemed to start at the ends of the beam and progress toward the center; it is apparent that corrosion proceeds along the center wire of the strands and would eventually cause the entire strand to corrode.

24. Corrosion products existed on the concrete adjacent to the strands in an amount dependent upon the degree of corrosion. All heavy staining of the concrete occurred at the ends of the beam where the corrosion was most pronounced (photograph 6c). Corrosion occurred at several places in the interior of the beam, but corrosion products in these cases were restricted to the immediate vicinity of the strand.

St. Augustine Beams

25. *Beam 10.* No sections of strands in beam 10 were directly exposed; however, it was clear because of the condition of the epoxy pads at the ends that the ends of the strands were not being protected. A 50-in.-long crack was present on one face of the beam; this crack ran along strands 7, 8, and 9 from the seaward end of the beam (photograph *7b*). Several rust-spotted areas along this crack indicated that water was getting through to the strands. On the opposite face of the beam (photograph *7a*), a 4-1/2-in.-long by 2-in.-wide area of corrosion products (31 to 36 in. from seaward end) verified that water was getting into the strands at this point. An 11-1/4-in.-long crack occurred in connection with this rusted area.

26. The following subparagraphs give the results of the examination of the steel strands from beam 10.

a. *Strand 1.*

(1) *Landward end.* Continuous external corrosion existed for 71 in. from end (heavy = 26 in., moderate = 26-1/2 in., light = 18-1/2 in.).

(2) *Seaward end.* Continuous external corrosion existed for 7 in. from end (heavy = 1 in., moderate = 3 in., light = 3 in.).

(3) *Rest of strand.* A 3-in. section of the strand, located 7 to 10 in. from the seaward end, was apparently rust free. Two wires were corroded into at a point 38 in. from the seaward end.

(4) *Internal versus external.* Internal corrosion extended through the entire strand, with the center wire having the most corrosion; other wires were corroded on the surfaces which were in contact with the center wire.

b. *Strand 2.*

(1) *Landward end.* Continuous external corrosion existed for 69 in. from end (heavy = 33-1/2 in., moderate = 11-1/2 in., light = 24 in.).

(2) *Seaward end.* Continuous external corrosion existed for 8 in. from end (heavy = 3-1/2 in., moderate = 2 in., light = 2-1/2 in.).

(3) *Rest of strand.* A 4-in. section of the strand, located 8 to 12 in. from the seaward end, was apparently rust free.

(4) *Internal versus external.* Internal corrosion extended through the entire strand, with the corrosion on the center wire being the heaviest. Other wires were corroded on surfaces which were in contact with the center wire.

c. *Strands 3 through 9.*

(1) *Entire length.* These strands (photograph 8) had continuous external corrosion for their entire length, as follows:

Strand	Extent of Indicated Level of Corrosion, in. Heavy	Moderate	Light	Some or All Wires Corroded into at These Places
3	34	32	15	7 in. from seaward end
4	31	39	11	43 in. from seaward end
5	25	48	8	23 in. from seaward end
6	26	40	15	35 in. from seaward end
7	32	42	7	35-3/4 in. from seaward end
8	52	25	4	35-3/4 in. from seaward end
9*	37	20	24	36 in. from seaward end

* Heavy deposits of corrosion products were on strand 9 at 40-1/2 and 42-1/2 in. from seaward end (photograph *8b*).

(2) *Internal versus external.* Internal corrosion existed through the entire strands, with the center wire having the most corrosion; other wires were corroded on the surfaces which were in contact with the center wire.

27. The external corrosion on the steel strands in beam 10 is summarized below:

Strand	Total External Corrosion in.	Total External Corrosion % of Total Length of Strand	Strand	Total External Corrosion in.	Total External Corrosion % of Total Length of Strand
1	78	96	6	81	100
2	77	95	7	81	100
3	81	100	8	81	100
4	81	100	9	81	100
5	81	100			

28. The extensive corrosion in beam 10 precluded the positive determination of the relationship between external corrosion and beam ends. A reasonable estimate would be that approximately one-third of the corrosion was associated with the beam ends while the other two-thirds resulted from the cracks.

29. The steel strands in beam 10 were essentially corroded for their entire length (only strands 1 and 2 had rust-free areas). The ineffectiveness of the epoxy pads caused strand corrosion at the ends, and the cracks which existed in the beam after loading allowed the strands to corrode for essentially their entire length. It is again apparent that corrosion proceeds along the center wire of each strand.

30. *Beam 18.* Beam 18 failed during the 1968 reloading operations and thus was in two pieces when received at the laboratory. All wires were broken and the beam consisted of a landward piece (about one-third of the beam) and a seaward piece (about one-third of the beam). The middle one-third (approximately 19 in.) of the beam was missing except for the strands; all of the concrete had spalled off in this middle section (photograph 9).

31. The epoxy pads were essentially intact on the two ends of beam 18, but the discoloration which could be seen through the pad indicated that rusting was taking place underneath. No tips of the strands were uncovered, but considerable portions of the strands were exposed in the failure area of this beam by spalling and disintegration of the concrete. The following tabulation summarizes the lengths of strand which were exposed directly to the elements.

	Inches of Strand Exposed				
			Failure Area		
Strand	Landward End	Seaward End	Landward Portion	Seaward Portion	Total
1	None	None	4-1/2	5-1/2	10
2*	None	None	9	2-1/4	11-1/4
3*	None	None	10	3	13
4	None	None	5	7	12
5	None	None	3-1/2	8	11-1/2
6	None	None	9-1/2	2	11-1/2
7	None	None	4-3/4	10	14-3/4
8	None	None	5-1/4	9	14-1/4
9*	None	None	14	3	17

* Approximately 3 in. of strand missing in failure area; this is included in exposed length.

32. The following subparagraphs give the results of the examination of the steel strands from beam 18.

a. *Strand 1.*

(1) *Landward end.* Continuous external corrosion existed for 6-1/2 in. from the end of the beam (heavy = 1/2 in., moderate = 2 in., light = 4 in.) and for 11 in. from the failure area (heavy = 5 in., moderate = 5 in., light = 1 in.). Photograph 10*a* shows the failure area of strand 1.

(2) *Seaward end.* Continuous external corrosion extended for only 1/2 in. (heavy) from the seaward end and for 15 in. (heavy = 7 in., moderate = 5 in., light = 3 in.) from the failure area.

(3) *Rest of strand.* A spot of moderate corrosion 1-1/2 in. long existed on the landward portion of the strand; this was located approximately 14 in. from the landward end. Intermittent corrosion extended for 20 in. on the seaward portion of the strand (heavy = 2 in., moderate = 10 in., light = 8 in.).

b. *Strand 2.*

(1) *Landward end.* Continuous external corrosion extended for 1/4 in. (heavy) from the end and for 20-1/2 in. (heavy = 10 in., moderate = 4 in., light = 6-1/2 in.) from the failure area.

(2) *Seaward end.* Continuous external corrosion existed for only 1/2 in. (heavy) from the end and for 4 in. (heavy = 3 in., moderate = 1 in.) from the failure area.

(3) *Rest of strand.* Intermittent corrosion existed for 26 in. (heavy = 11 in., moderate = 10 in., light = 5 in.) on the rest of the strand.

c. *Strand 3.*

(1) *Landward end.* Continuous external corrosion extended for about 1/4 in. (heavy) from the landward end and for 21 in. (heavy = 10-1/2 in., moderate = 6 in., light = 4-1/2 in.) from the failure area. Photograph 10*b* shows the landward end of strand 3.

(2) *Seaward end.* Continuous external corrosion existed for about 4-1/4 in. (heavy = 1/2 in., moderate = 1-3/4 in., light = 2 in.) from the end of the beam and for about 4 in. (heavy = 3 in., moderate = 1 in.) from the failure area.

(3) *Rest of strand.* Intermittent corrosion extended for a total of 18-1/4 in. (heavy = 2 in., moderate = 7 in., light = 9-1/4 in.) on the rest of the strand.

d. *Strand 4.*

(1) *Landward end.* Continuous external corrosion extended for only 1/2 in. (heavy) from the landward end and for 21 in. (heavy = 10-1/2 in., moderate = 6 in., light = 4-1/2 in.) from the failure area. Photograph 10*c* shows the failure area of strand 4.

(2) *Seaward end.* Continuous external corrosion existed for 2 in. from the end of the beam (heavy = 1/4 in., moderate = 1/2 in., light = 1-1/4 in.) and for 12 in. from the failure area (heavy = 9 in., moderate = 2 in., light = 1 in.).

(3) *Rest of strand.* Intermittent corrosion extended for a total of 29 in. (heavy = 9 in., moderate = 5 in., light = 15 in.) on the rest of the strand.

e. *Strand 5.*

(1) *Landward end.* Continuous external corrosion existed for 1/2 in. (heavy) from the landward end and for 14 1/2 in. (heavy = 6 in., moderate = 5 in., light = 3-1/2 in.) from the failure area.

(2) *Seaward end.* Continuous external corrosion extended for 1-1/2 in. (heavy = 1/2 in., light = 1 in.) from the seaward end and for 12 in. (heavy = 8 in., moderate = 3 in., light = 1 in.) from the failure area.

(3) *Rest of strand.* Intermittent corrosion existed for 21-1/2 in. (heavy = 1 in., moderate = 9-1/2 in., light = 11 in.) on the rest of the strand (photograph 10*d*).

f. *Strand 6.*

(1) *Landward end.* Continuous external corrosion existed for only 1/2 in. (heavy) from the end and for 15-1/2 in. (heavy = 11 in., moderate = 2-1/2 in., light = 2 in.) from the failure area.

(2) *Seaward end.* Continuous external corrosion extended for 1/2 in. (heavy) from the seaward end and for 9 in. (heavy = 6 in., moderate = 2 in., light = 1 in.) from the failure area.

(3) *Rest of strand.* Intermittent corrosion existed for a total of 20 in. (heavy = 2 in., moderate = 12 in., light = 6 in.) on the rest of the strand.

g. *Strand 7.*

(1) *Landward end.* Continuous external corrosion existed for 12-1/2 in. (heavy = 1/4 in., moderate = 5 in., light = 7-1/4 in.) from the end of the beam and for 8 in. (heavy = 5 in., moderate = 1 in., light = 2 in.) from the failure area.

(2) *Seaward end.* Continuous external corrosion extended for 1-1/2 in. (equally divided between heavy, moderate, and light) from the seaward end of the beam and for 17 in. (heavy = 11 in., moderate = 3 in., light = 3 in.) from the failure area.

(3) *Rest of strand.* Intermittent corrosion existed for 22 in. (heavy = 1 in., moderate = 11 in., light = 10 in.) on the rest of the strand.

h. *Strand 8.*

(1) *Landward end.* Continuous external corrosion existed for only 1/4 in. (heavy) from the landward end of the beam and for 10-1/2 in. (heavy = 10 in., light = 1/2 in.) from the failure area (photograph 10*e* and *f*).

(2) *Seaward end.* Continuous external corrosion extended for only about 1/4 in. (heavy) from the seaward end and for 15-1/2 in. (heavy = 14-1/2, light = 1 in.) from the failure area.

(3) *Rest of strand.* Intermittent corrosion existed for a total of 20 in. (heavy = 2 in., moderate = 9 in., light = 9 in.) on the rest of the strand.

i. *Strand 9.*

(1) *Landward end.* Continuous external corrosion existed for 1/4 in. (heavy) from the landward end of the beam (photograph 10*g*) and for 18 in. (heavy = 16 in., moderate = 1 in., light = 1 in.) from the failure area.

(2) *Seaward end.* Continuous external corrosion extended for 1/4 in. (heavy) from the end of the beam and for 14 in. (heavy = 13 in., moderate = 1 in.) from the failure area.

(3) *Rest of strand.* Intermittent corrosion existed for a total of 15-1/2 in. (heavy = 1 in., moderate = 7-1/2 in., light = [illegible] in.) on the rest of the strand.

33. Internal corrosion was found to extend farther than external corrosion in all strands from beam 18. More corrosion was evident on the center wire, and the other wires were corroded on surfaces which were in contact with the center wire.

34. The following tabulation summarizes the external corrosion found on the steel strands in beam 18.

Strand	Total External Corrosion		External Corrosion Associated with Ends of Beam		External Corrosion Associated with Failure Areas		External Corrosion Associated with Remainder of Beam	
	in.	% of Total Length of Strand	in.	% of Total External Corrosion	in.	% of Total External Corrosion	in.	% of Total External Corrosion
1	54-1/2	67	7	13	26	48	21-1/2	39
2	51-1/4	63	3/4	1	24-1/2	48	26	51
3	47-3/4	59	4-1/2	9	25	52	18-1/4	39
4	64-1/2	80	2-1/2	4	33	51	29	45
5	50	62	2	4	26-1/2	53	21 1/2	43
6	45-1/2	56	1	2	24-1/2	54	20	44
7	61	75	14	23	25	41	22	36
8	46-1/2	57	1/2	1	26	56	20	43
9	48	59	1/2	1	32	67	15-1/2	32

35. The corrosion of the steel strands in beam 18 appears to be largely due to the cracks which were induced in the beam at loading. The cracks which were formed at loading (in 1959) apparently allowed water to get into the strands and start the corrosion. This corrosion caused the beam to fail in 1968. When corrosion started in the strands, it proceeded down the center wire of each strand since the internal corrosion extended farther than the external corrosion in each strand. The epoxy pads were not particularly effective in preventing the start of corrosion at the ends, but in beam 18 the corrosion associated with the ends of the beam is but a small portion (1 to 23 percent) of the total corrosion. After the beam failed in 1968, the subsequent spalling and disintegration of the concrete in the failure area uncovered considerable lengths of the steel strand (10 to 17 in.) and left these portions exposed directly to the elements.

TENSILE STRENGTH AND ELASTIC PROPERTIES OF STRANDS

36. Six or seven strand sections from each of the four beams were tension tested to determine their ultimate tensile strength. In addition, the total elongation and stress-strain properties of some of the strands were determined. These tests were conducted generally in accordance with the applicable portions of ASTM Designation: A 416-68[3] and the results were compared with the stated specifications for this type of prestressing strand:

<u>ASTM A 416-68 Specifications</u>

Minimum load at 1% extension = 7650 lb
Minimum ultimate load = 9000 lb
Minimum total elongation = 3.5%

Treat Island Beams

37. *Beam 4.* Seven sections of strand from beam 4 were tested for tensile strength; only

one section of strand (No. 2) met the ultimate strength requirements of ASTM A 416-68. The results obtained are given below.

Strand	Ultimate Load, lb	Ultimate Stress, psi	Strand	Ultimate Load, lb	Ultimate Stress, psi
1	8750*	245,785	6	8550*	240,170
2	9125	256,320	7	8475*	238,060
4	8150*	222,935	8	7950*	223,315
5	8125*	228,230			

* Did not meet minimum ASTM requirement.

38. *Beam 8.* Six sections of strand from beam 8 were tension tested; stress-strain properties and total elongation were determined. All strand sections met the specifications except the section from strand 1. Results were as follows:

Strand	Ultimate Load, lb	Ultimate Stress, psi	Load at 1% Extension, lb	Total Elongation, %
1	5,900*	165,730	--	0.60*
2	10,130	284,550	8800	5.54
4	10,260	288,200	9400	6.20
5	9,900	278,090	9000	3.72
8	10,330	290,170	8800	5.61
9	10,180	285,955	8800	5.67

* Did not meet requirements of ASTM specification.

A typical stress-strain curve obtained on a strand from beam 8 which met the ASTM requirements is given in plate 1*a*.

St. Augustine Beams

39. *Beam 10.* Six strand sections from beam 10 were tension tested; none of the sections met the requirements of the ASTM test. Data obtained are given below.

Strand	Ultimate Load lb	Ultimate Stress psi	Load at 1% Extension, lb
1	3900*	109,550	**
2	2620*	73,595	**
3	4110*	115,450	**
4	5600*	157,305	**
5	2500*	70,225	2450*
6	2300*	64,605	2200*

* Did not meet requirements of ASTM specification.
** Did not undergo 1 percent extension.

40. *Beam 18.* Six strand sections from beam 18 were tension tested; only one section (strand 9) met the requirements in the ASTM specification. Results are given on the following page.

Strand	Ultimate Load, lb	Ultimate Stress, psi	Load at 1% Extension, lb	Total Elongation, %
1	6,920*	194,380	**	--
2	4,760*	133,710	**	--
4	8,550*	240,170	7650	2.40*
6	6,160*	173,035	**	--
7	4,080*	114,605	**	--
9	10,240	287,640	8700	5.20

* Did not meet requirements of ASTM specification.
** Did not undergo 1 percent extension.

The stress-strain curve obtained on strand 9, which was the only strand which met the ASTM specification, is given in plate 1*b*.

DEPTH OF CARBONATION

41. Three 4-1/2- by 9-in. cross sections, each formed by a different saw cut, from three of the four concrete beams were color tested with a 1 percent anhydrous phenolphthalein solution to reveal the depth of carbonation. Areas which have been carbonated do not change color after the solution is applied to them, while uncarbonated areas turn red because of alkalinity. The locations of these cross sections in the various beams are shown below.

Beam	Cross Section	Distance in In. from Landward End of Beam	Distance in In. from Seaward End of Beam
		Treat Island Beam	
8	A	21	60
8	B	70	11
8	C	74-1/2	6-1/2
		St. Augustine Beams	
10	1	31	50
10	2	14	67
10	3	9	72
18	A	76	5
18	B	56	25
18	C	71	10

Note: Depth of carbonation tests were not conducted on beam 4.

42. Photograph 11 shows typical beam sections before and after staining with the test solution. It should be noted that the aggregate pieces in the concrete show as white after color testing since they are limestone (carbonate) aggregates. The depth of carbonation in all sections tested appeared to be 1/32 in. (photograph 11*b*) or less from the outer surface. The effect of carbonation on the corrosion of the steel strands in these beams is therefore negligible.

DEPTH OF CHLORIDE PENETRATION

43. Concrete slices (1/4 in. thick) were cut from three of the four beams (no samples were

run from beam 4) at depths of 1/2, 1, 2, and 2-1/4 in. from the surface. These slices were cut with a diamond saw which was lubricated with a special oil to avoid contamination of the concrete specimens. The concrete slices were analyzed chemically for total chloride content by a potentiometric titration method.[4,5] The locations of the samples taken from the beams and the total chloride contents are given in the tabulation below.

			Distance in In. from		Total Chlorides, %	
Beam	Slice	Depth from Nearest Surface of Beam, in.	Landward End of Beam	Seaward End of Beam	By Weight Of Sample	By Weight of Cement in Sample
			Treat Island Beam			
8	4	1/2	72-1/2	8-1/2	0.44	2.71
	3	1			0.25	1.55
	2	2			0.14	0.85
	1	2-1/4			0.14	0.83
			St. Augustine Beams			
10	102	1/2	27	54	0.32	1.96
	103	1			0.20	1.20
	104	2			0.25	1.52
	101	2-1/4			0.30	1.84
	202	1/2	11-1/2	69-1/2	0.22	1.33
	204	1			0.18	1.13
	201	2			0.07	1.02
	203	2-1/4			0.20	1.26
18	4	1/2	73-1/2	7-1/2	0.29	1.76
	3	1			0.25	1.53
	2	2			0.24	1.49
	1	2-1/4			0.25	1.53
	8	1/2	58-1/2	22-1/2	0.30	1.87
	5	1			0.20	1.26
	6	2			0.23	1.42
	7	2-1/4			0.31	1.91

Note: Depths of 2 and 2-1/4 in. are in the immediate proximity of the steel strands.

44. Total chloride contents obtained ranged from 0.83 percent by weight of cement at the center of beam 8 (2-1/4 in. from surface) to 2.71 percent at a depth of 1/2 in. from the surface of beam 8. The chloride contents of the St. Augustine beams (10 and 18) ranged from 1.02 to 1.96 percent by weight of cement. Plate 2 depicts the chloride distribution graphically. The curve for beam 8 (plate 2*a*) shows a decrease in chloride content as the depth increased. The other curves have an upturn (increase in chloride content) at the 2- and 2-1/4-in. depths; this indicates that the steel strands, which are in the immediate proximity of the 2- and 2-1/4-in. depths, are influencing the chloride content. Moisture migration along or inside the strands has evidently increased the chloride content at these depths in the two beams from St. Augustine.

PART IV: CONCLUDING REMARKS

TREAT ISLAND BEAMS

45. The steel strands from beams 4 and 8 were corroded externally for 20 to 63 percent of their entire length. Most of this corrosion was associated with the ends of the beams where the loss of the end protection (epoxy pads) and subsequent spalling had allowed corrosion to begin. All heavy staining of the concrete with corrosion products occurred near the beam ends. Internal strand corrosion seemed to progress along the center wire from the ends of the beam and extended generally well beyond the external corrosion on the strands.

46. Seven of thirteen strand sections from beams 4 and 8 met the minimum ultimate load requirements of ASTM Designation: A 416-68. The strand sections tested represented the best portions of the strands from these beams since the most heavily corroded end sections were unraveled for determination of internal corrosion.

47. Carbonation was apparently not a factor in the corrosion of the strands in the Treat Island beams. Depths of carbonation were 1/32 in. or less.

48. Depth of chloride penetration tests were conducted on beam 8 only, and these tests revealed that sufficient chlorides were present throughout the beam, in the slices tested, to cause corrosion on the prestressing strands (0.83 to 2.71 percent by weight of cement). The migration of moisture along and in the strands had not progressed to the point to significantly influence the chloride content at the steel strands in the slices which were tested.

49. Beam 8 strands were corroded externally to a greater degree than were the beam 4 strands; 51 percent (average) of the total length of strands in beam 8 had external corrosion compared to 28 percent (average) in beam 4. The strand sections of beam 8 which were tension tested, however, took a greater ultimate load than did the strand sections from beam 4. The fact that the strands in beam 8 were pretensioned at fabrication while those of beam 4 were not pretensioned appreciably could be a factor in this difference.

ST. AUGUSTINE BEAMS

50. The steel strands from beams 10 and 18 were corroded externally for 56 to 100 percent of their entire length. Some of this corrosion was associated with the ends of the beams due to the ineffectiveness of the epoxy pad end protection, but the major portion of the corrosion seemed to be associated with the water ingress to the strands through the cracks which were formed at initial loading. Beam 18 failed during reloading operations in 1968; the strands in the middle one-third of the beam failed due to corrosion. The strands in beam 10 were generally more heavily corroded than those in beam 18, which indicates that most of the corrosion in the beam 10 strands took place since 1968; otherwise, beam 10 would have been the first to fail under load. The severe corrosion of the strands in the middle one-third of beam 18, which caused the beam failure, took place prior to 1968. Internal strand corrosion seemed to progress along the center wire of each strand and was more extensive than the external corrosion.

51. The steel strands from the St. Augustine beams were in poorer condition than the strands from the Treat Island beams. Only 1 of the 12 strand sections from beams 10 and 18 met the requirements of ASTM Designation: A 416-68.

52 Carbonation was apparently not a factor in the corrosion of the strands in the St. Augustine beams, as depths of carbonation were negligible.

53. Depth of chloride penetration tests revealed that sufficient chlorides were present throughout the beams to cause corrosion of the strands. The high chloride contents obtained in the immediate proximity of the strands in beams 10 and 18 indicated that moisture migration along and in the strands was a significant factor. Chloride contents ranged from 1.02 to 1.96 percent by weight of cement.

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a. Beam 4, landward end

b. Beam 4, seaward end

c. Beam 8, landward end

d. Beam 8, seaward end

Photograph 1. Beams 4 and 8 on beach at Treat Island, Maine

a. Beam 4, landward end

b. Beam 4, seaward end

c. Beam 8, landward end

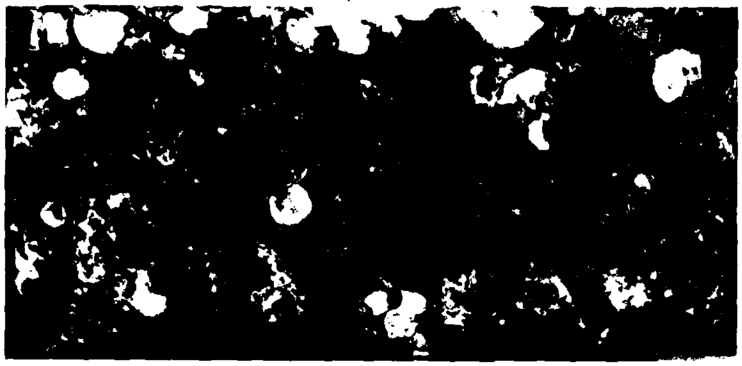
d. Beam 8, seaward end

Photograph 2. End views of beams 4 and 8

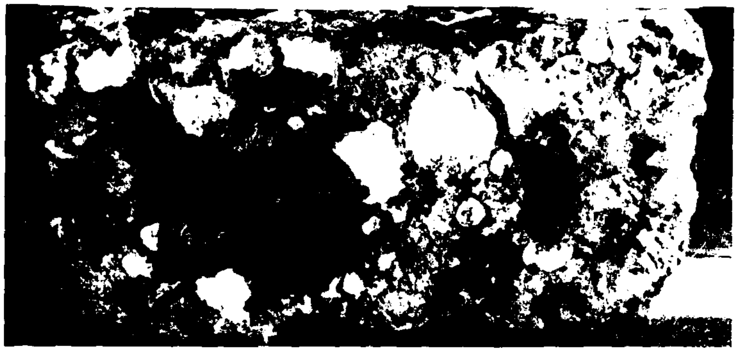
a. Beams 10 and 18 with yoke after failure of beam 18 (on left)

b. Close-up of failure area, beam 18

Photograph 3. Beams 10 and 18 at St. Augustine, Florida

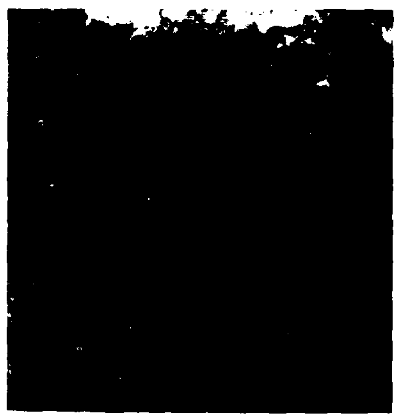


a. Landward end, beam 10



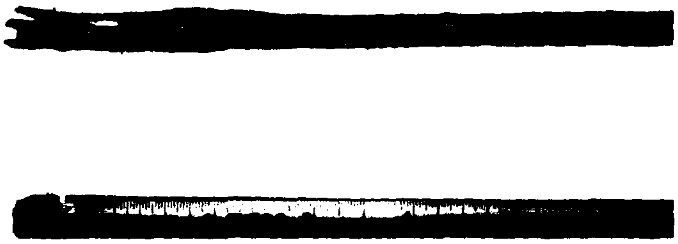
b. Seaward end, beam 10

c. Landward end, beam 18

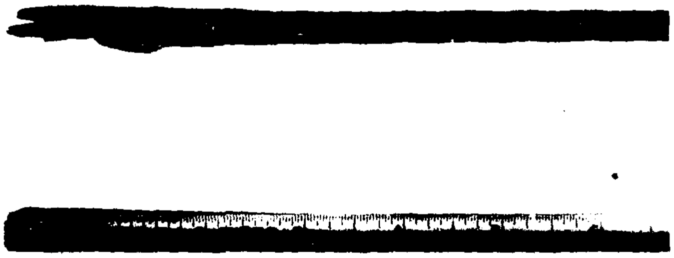


d. Seaward end, beam 18

Photograph 4. End views of beams 10 and 18



a. Beam 4, strand 6, landward end



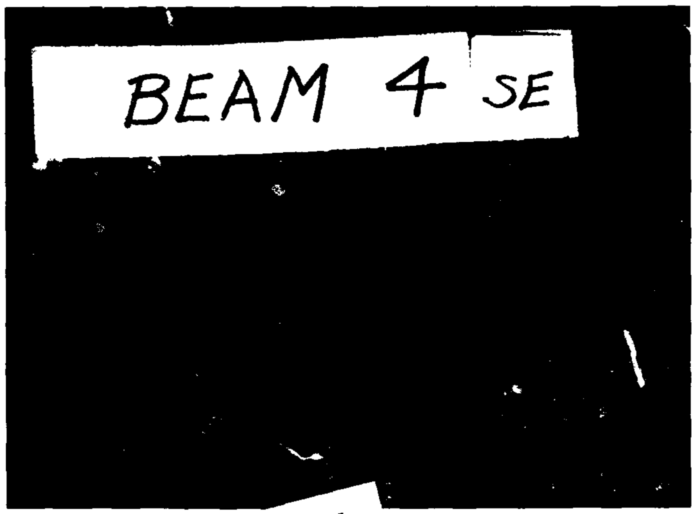
b. Beam 4, strand 9, landward end

c. Beam 8, strand 6, landward end

d. Beam 8, strand 9, landward end

Photograph 5. Strands from beams 4 and 8

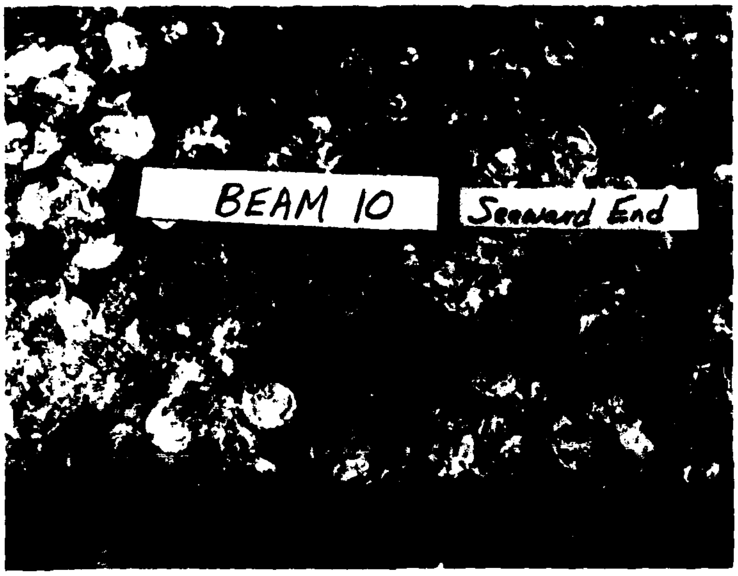
a. Beam 4, seaward end, at strands



b. Beam 4, seaward end, deposit of corrosion products

c. Beam 8, landward end

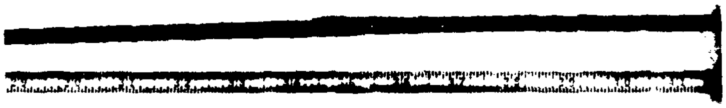
Photograph 6. Corrosion products on beams 4 and 8



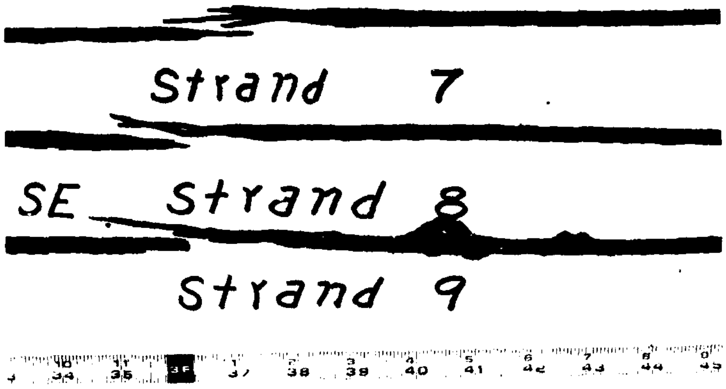
a. Rust spot and crack over strands
(strands at bottom in this view)

b. Crack viewed from opposite side
(strands at top in this view)

Photograph 7. Closeup views of crack at approximately midlength in beam 10



a. Strand 6, 29 to 41 in. from seaward end



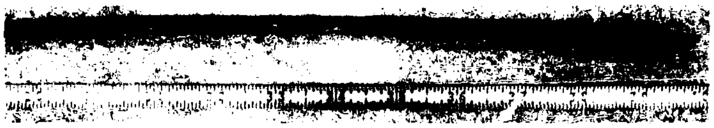
b. Strands 7, 8, and 9, 33 to 45 in.
from seaward end

Photograph 8. Strands from beam 10

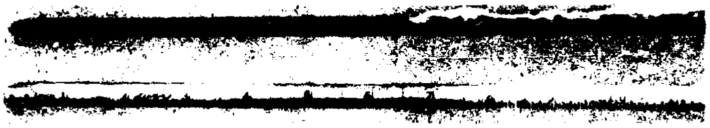
a. Landward portion

b. Seaward portion

Photograph 9. Close-ups of failure area, beam 18

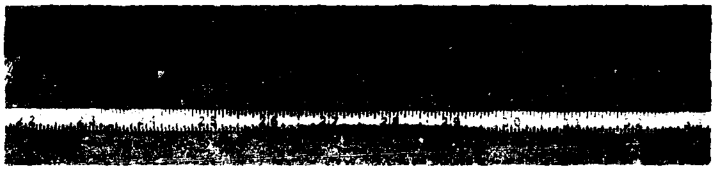


a. Strand 1, failure area, landward portion

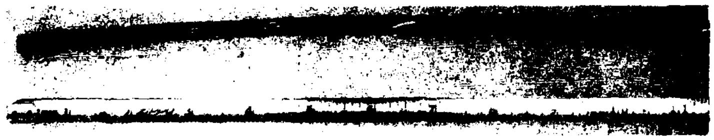


b. Strand 3, landward end

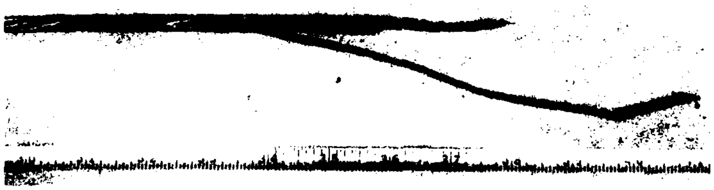
c. Strand 4, failure area, landward portion



d. Strand 5, intermittent corrosion, landward portion



e. Strand 8, landward end

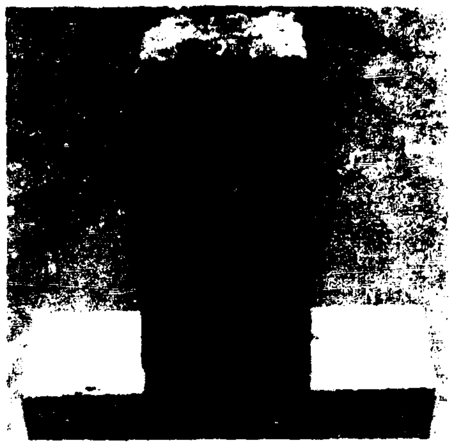


f. Strand 8, failure area, landward portion

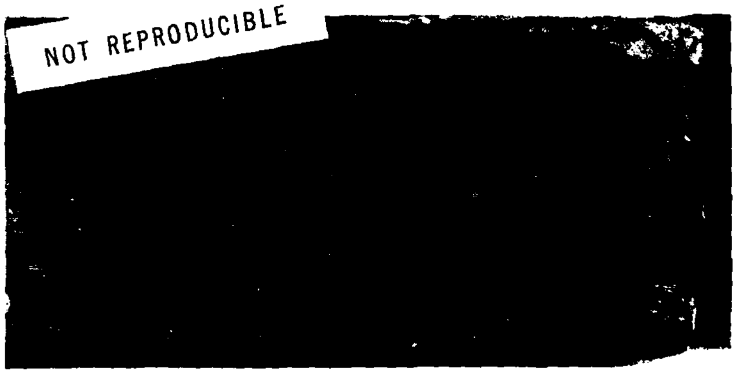
g. Strand 9, landward end

Photograph 10. Strands from beam 18

a. Beam 8, section A, before



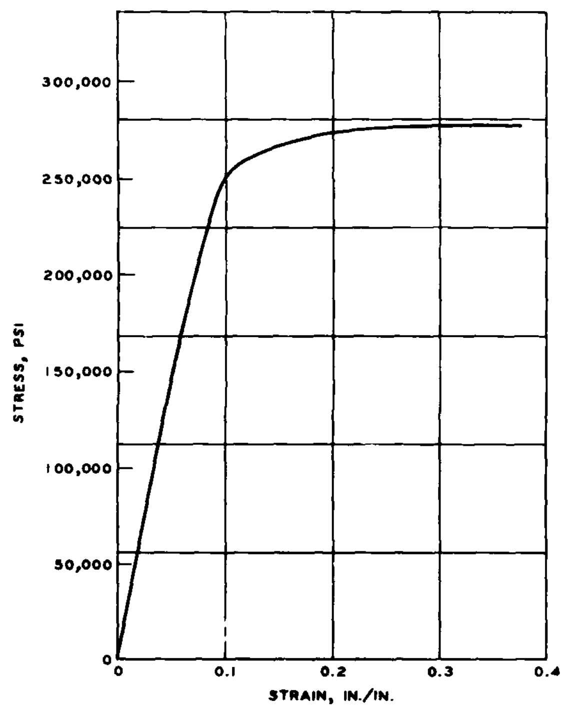
b. Beam 8, section A, after



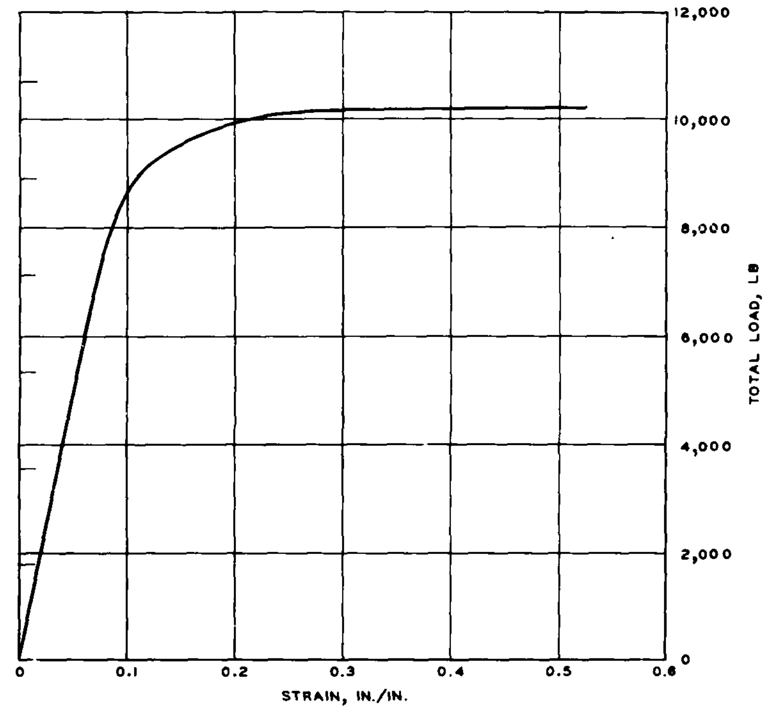
c. Beam 10, section 3, before

d. Beam 10, section 3, after

Photograph 11. Cross sections of beams 8 and 10 before and after color testing

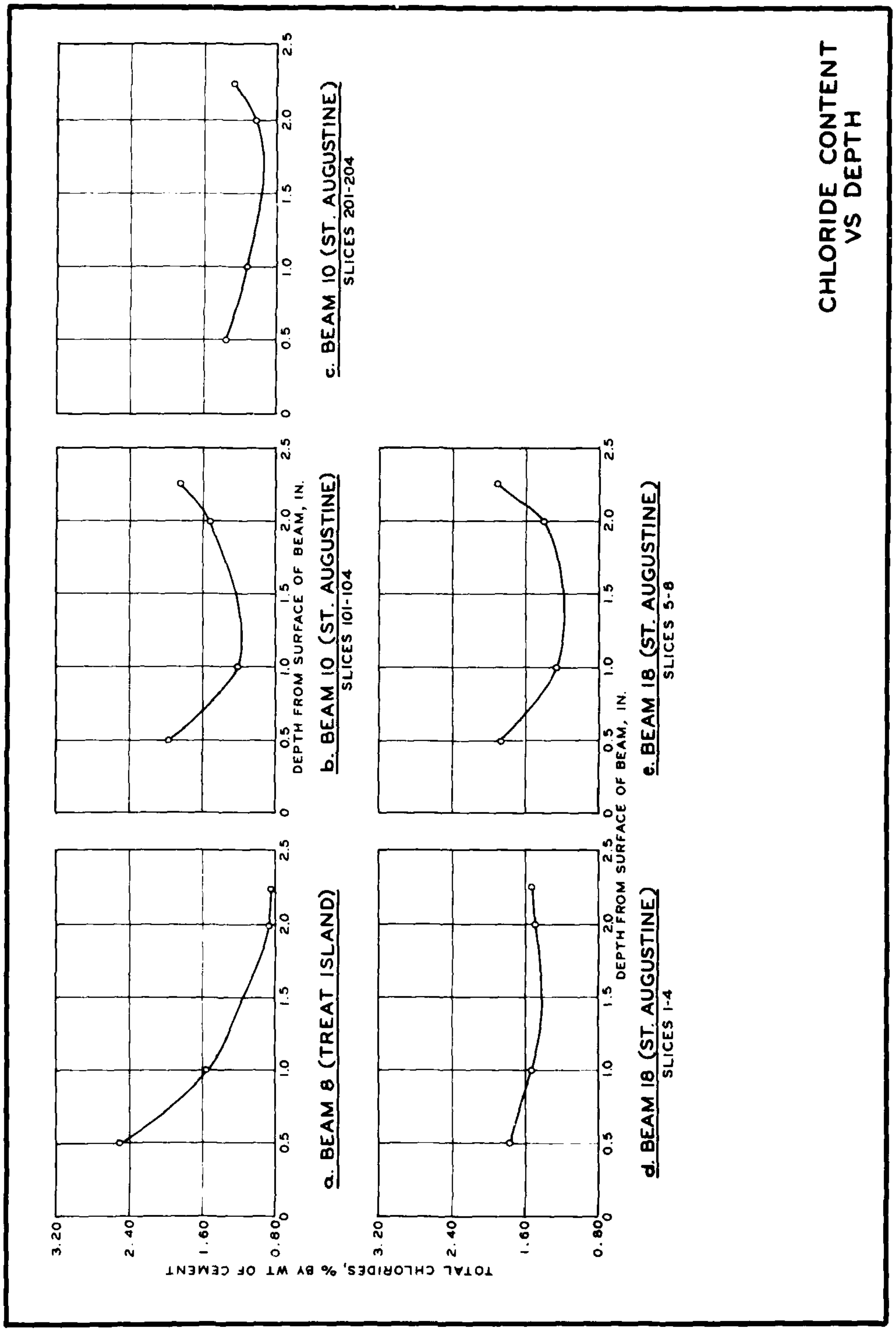


a. BEAM 8, STRAND 5
(TREAT ISLAND)



b. BEAM 18, STRAND 9
(ST. AUGUSTINE)

STRESS–STRAIN CURVES



CHLORIDE CONTENT
VS DEPTH

PLATE 2